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Hollow-Cathode Development for Use as a CW Plasma Source

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NRL is developing a Large Area Plasma Processing System (LAPPS) for materials processing applications. The goal is to develop a uniform plasma source that is 100 cm by 100 cm in size. The plasma generation technique utilizes a sheet electron beam to ionize a low density, neutral background gas (oxygen, nitrogen, argon, or neon). The beam electrons are generated by a separate cathode located outside the processing region and confined to a narrow channel by a transverse magnetic field of 100-300 Gauss. Plasma production is confined to the beam channel and can be pulsed or continuous. Pulsed beams have been produced at up to 5 keV and 20 mA/cm using a 60 cm long by 1.9 cm diameter cylindrical hollow-cathode. Continuous beams have been produced at up to 6 keV using both cylindrical and rectangular hollow-cathodes operated at low voltage (200-400 V) followed by a high-voltage acceleration stage. These electrons have a propagation range of several hundred cm in the neutral gas background within the 20-200 mTorr operating pressure range of the system. This paper will describe the development work to date on cathodes for the continuous source.

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Hollow-Cathode Development for use as a CW Plasma Source[†]

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Abstract

NRL is developing a Large Area Plasma Processing System (LAPPS) for materials processing applications. The goal is to develop a uniform plasma source that is 100 cm by 100 cm in size. The plasma generation technique utilizes a sheet electron beam to ionize a low density, neutral background gas (oxygen, nitrogen, argon or neon). The beam electrons are generated by a separate cathode located outside the processing region and confined to a narrow channel by a longitudinal magnetic field of 100-300 Gauss. Plasma production is confined to the beam channel and can be pulsed or continuous. Pulsed beams have been produced at up to 5 keV and 20 mA/cm^2 using a 60 cm long by 1.9 cm diameter cylindrical, hollow-cathode (HC). Continuous beams have been produced at up to 6 keV using both cylindrical and rectangular hollow-cathodes operated at low voltage (200-400 V) followed by a high-voltage acceleration stage. These electrons have a propagation range of several hundred cm in the neutral gas background within the 20-200 mTorr operating pressure range of the system. This paper will describe the development work to date on cathodes for the continuous source.

Introduction

Sheet plasmas (60 cm x 60cm x 1 cm thick) produced by pulsed electron beams from long, HC sources were used as microwave reflectors in the Agile Mirror experiment.[1,2,3] While the pulsed source produced some electron beam over a wide range of magnetic field and gas pressures (10-350 gauss and 20-70 mTorr), it only generated a high density plasma sheet in a very narrow parameter regime which was dubbed the Enhanced Glow mode of operation. The pulse length for that cathode source varied from a few hundred μs to a few ms during a single pulse. The pulsed cathodes utilize secondary emission of electrons from a linear hallow-cathode. A high voltage sheath is established near the cathode's metal surface. Ions bombarding the surface at the cathode sheath energy liberate electrons. These electrons cross the sheath and form the desired electron beam. Because of the inefficiency of the secondary emission process, a considerable amount of energy is deposited in the cathode, requiring cooling and severely limiting duty cycle. In addition, material from the cathode surface is sputtered into the vacuum chamber

[†] Work supported by the Office of Naval Research.

[1] J. Mathew, Rev. Sci. Instrum. **65**, 3756 (1994).

[2] R. F. Fernsler, W. M. Manheimer, R. A. Meger, J. Mathew, D. P. Murphy, R. E. Pechacek and J. A. Gregor, Phys. Plasmas **5**, 2137 (1998).

[3] D. P. Murphy, R. F. Fernsler and R. A. Meger, NRL Memo Report NRL/MR/6754-99-8368.

Manuscript approved August 14, 2000.

resulting in contamination and coating issues. The secondary emission process also relies on the background gas to generate the incident ion flux. Thus the cathode behavior depended on the gas density and to some extent on the gas species. For all of these reasons the pulsed HCs are unsuitable for high duty cycle plasma processing applications.

In 1999 Burdovitsin and Oks[4] (henceforth B&O) described a HC plasma source that operated continuously (CW). It consisted of a cylindrically symmetric, low-voltage, HC discharge followed by a high-voltage acceleration stage, all immersed in an external magnetic field. A wire mesh grid formed the interface between the two sections of the source. It prevented the high electric field of the acceleration stage from penetrating and disrupting the hollow cathode but was porous enough to permit electrons from the discharge cloud to enter the acceleration region. The HC was a closed cylinder 50 mm wide by 100 mm long with a 16 mm diameter hole in one end. A copper plate with a mesh covered 16 mm hole was spaced 10 mm from the cylinder. A second copper plate with an open 16 mm hole was spaced another 10 mm beyond the first plate (see Fig. 1). The fundamental difference between the pulsed HC and the B&O cathode is the production of free electrons at relatively low voltage. The –400 V used to drive the glow discharge in the HC section was sufficient to extract electrons from the cathode surface without large amounts of sputtering. The decoupling of the HC discharge from the acceleration stage allows one to independently tune the electron source for operations in different gases or at different gas densities. Once one established the HC discharge, the extraction voltage can be modulated if the equivalent to the pulsed HC source is desired. Based on this layout for a CW plasma source, we have designed and built four successively larger plasma sources, all leading up to the eventual deployment of a 100 cm wide source for LAPPS.

Four Generations of CW Plasma Sources

So far all four of the CW plasma sources developed for this application have been mounted in an aluminum vacuum chamber 50 cm diameter by 50 cm long for testing (see Fig. 2). The chamber can be filled with background gas at pressures of 20 mTorr and up. The fill gases utilized so far are air, argon, nitrogen and oxygen. The high voltage power supply can provide 1 A at 5000 V and the low voltage supply can provide 250 mA at 500 V. Since the low voltage supply "floats" at the high voltage supply's potential, it is electrically isolated from ground with a high voltage isolation transformer. The diagnostic suite includes beam current and voltage, plasma temperature and density and magnetic field strength.

[4] V. Burdovitsin and E. Oks, Rev. Sci. Instrum. **70**, 2975 (1999).

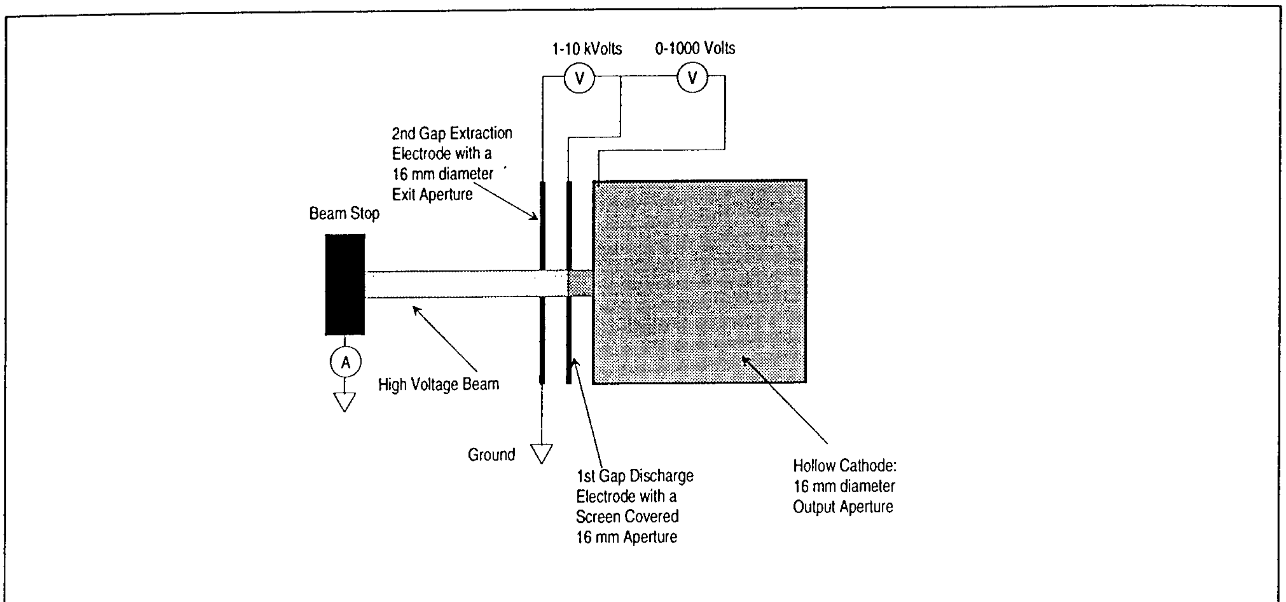

Figure 1. Schematic of the type of CW HC source designed by Burdovitsin and Oks.

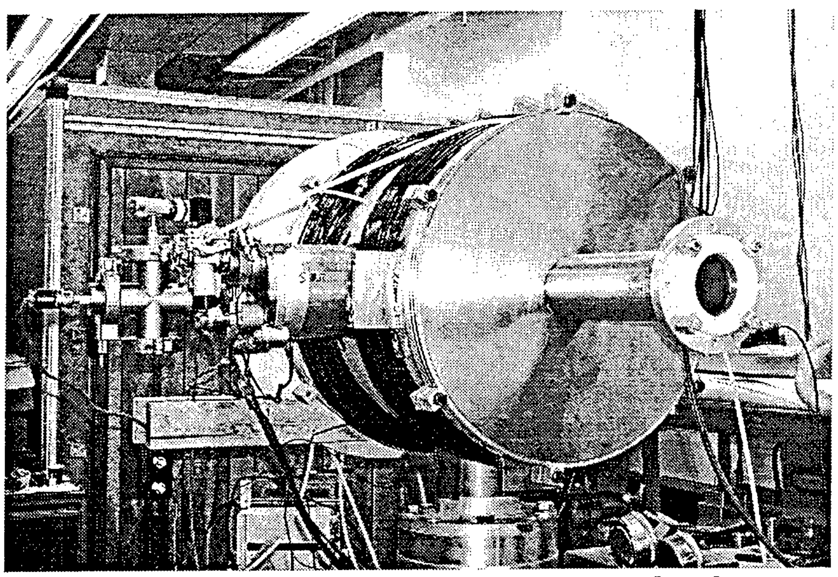

Figure 2. Aluminum test chamber for CW plasma source development. Magnetic field coils are mounted on the outside of the chamber.

1 cm Cylindrical Source

The first design tested was a cylindrically symmetric cathode, very similar to that in the B&O paper (see Figs. 3 & 4). It was an aluminum cylinder 10 cm diameter by 15 cm long with a 1 cm circular aperture in one end. Both the 1st gap discharge electrode and the 2nd gap acceleration electrode were made of brass with 1 cm circular apertures. The 1st electrode aperture was covered with a 50x50/inch, 30% transparent, stainless steel mesh (0.28 mm openings). B&O used a nearly identical mesh, but made of tantalum.

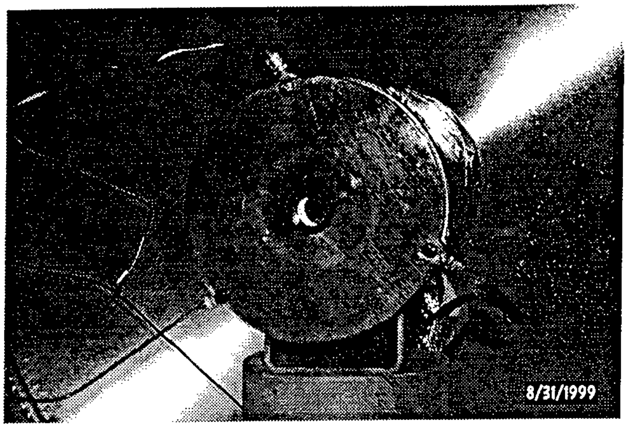

Figure 3. Front view of the 1 cm diameter aperture in the acceleration electrode. This front electrode is grounded to the chamber wall.

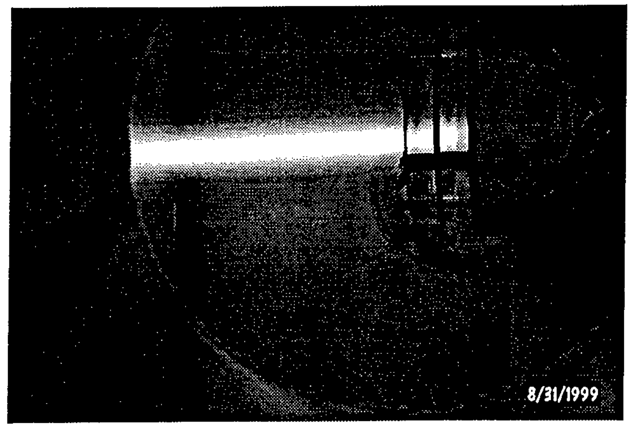

Figure 4. Side view of the circularly symmetric plasma generated by the electron beam from the CW HC. B=100 gauss, P=60 mTorr Air, V1=350 V and V2=1000 V.

The discharge current (1^{st} gap) was up to 200 mA. With an acceleration voltage of 1000 V, the 2^{nd} gap current was typically 100 mA. The current reaching the beam stop 25 cm downstream was about 70 mA. When the acceleration voltage was raised to 1250 V, the stainless steel beam stop would glow red hot at the point of contact. This cathode operated CW in air between pressures of 40-70 mTorr and a magnetic field of 100 gauss. Frequently, the cathode would not self-start at these pressures. We would then momentarily raise the chamber pressure to ~200 mTorr to get the HC discharge to initiate.

4 cm x 1 cm Slotted Source

The second generation replaced the circular apertures with 4 cm x 1 cm slotted apertures (see Fig. 5). The LAPPS source must have a long, thin aspect ratio, so this was the start in that direction. Again we measured the discharge current, the acceleration gap current and the beam stop current. We found, as did B&O, that the 2^{nd} gap current was limited to a value less that the 1^{st} gap current. Apparently, the source can not provide more current than that in the HC discharge. Figure 6 is a plot of 2^{nd} gap current and the beam stop current as a function of accelerating voltage for a fixed 1^{st} gap current of 150 mA. The external magnetic field is set at 90 gauss and the fill gas is air at pressures of 30-60 mTorr. As the acceleration voltage is raised, more of the beam reaches the beam stop. The range of a 1000 V electron in 60 mTorr of air is about 50 cm. The beam stop is shunted to ground through a 5 ohm resistor for monitoring purposes. The beam profile, shown in Figure 7, was measured using the current collected by an interceptive probe 5 cm downstream of the aperture, as seen in Figure 5. The probe is also shunted to ground through a 5 ohm monitoring resistor. The beam profile is not uniform across the slot. It can be peaked on center or peaked at the ends, depending on several parameters. Different wire meshes were tested, some courser (20x20/in) and some much finer (500x500/in) but the 50x50/in worked the best. Figures 8 and 9 show views of the source and the plasma it generates with the slot turned vertically. The beam intensity is peaked at the ends of the slot in this photo.

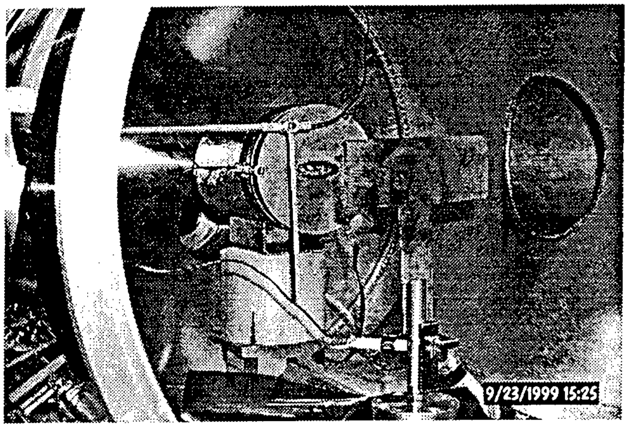

Figure 5. Modified CW plasma source with 4 cm x 1 cm slotted apertures.

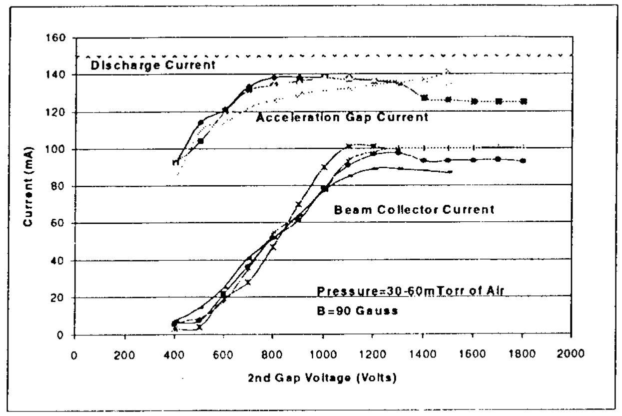

Figure 6. 2nd gap current and beam stop current as a function of 2nd gap voltage.

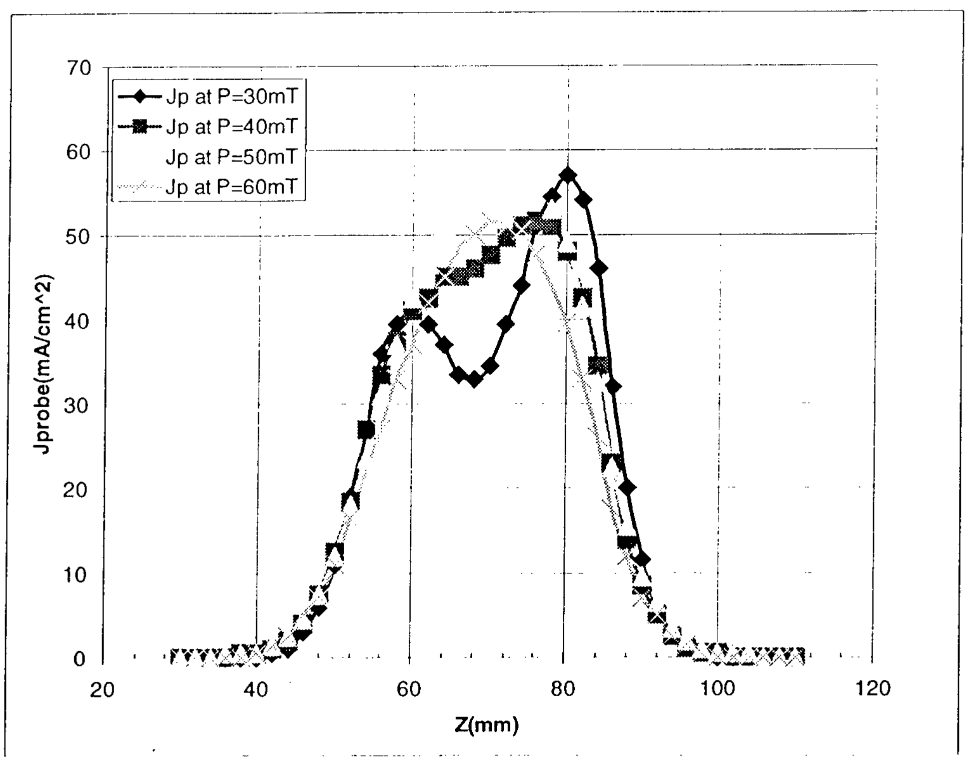

Figure 7. Beam profiles measured by an interceptive probe downstream of the 4 cm x 1 cm aperture plasma source.

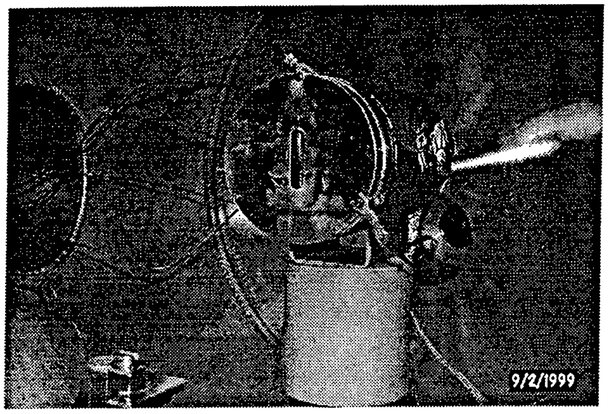

Figure 8. End view of the plasma source with 4 cm x 1 cm apertures.

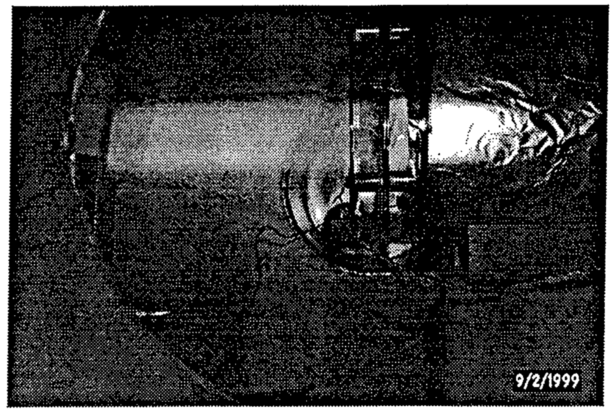

Figure 9. Side view of the plasma generated by the slotted cathode. The beam intensity is stronger at the top and bottom edges of the aperture.

10 cm x 1 cm Slotted Source

The third iteration of the CW source included 10 cm x 1 cm apertures. That system was mounted externally on one end flange of the vacuum chamber (see Fig. 10). An external solenoid was placed around the vacuum housing to extend the magnetic field inside the test chamber around the external source housing. Since the apertures in the system permitted the free flow of gas from the test chamber into the cathode housing, the hollow cathode operated with the same fill gas and pressure as the test chamber. The 20 cm diameter by 25 cm high structure allowed variously shaped HC designs to be mounted inside. Figure 11 shows a diagram of the third generation of CW HC system. Figure 12 shows a 3" x 4" x 6" aluminum box forming the HC inside the vacuum housing.

Figure 10. External solenoid and vacuum housing for the 10 cm x 1 cm slotted HC system.

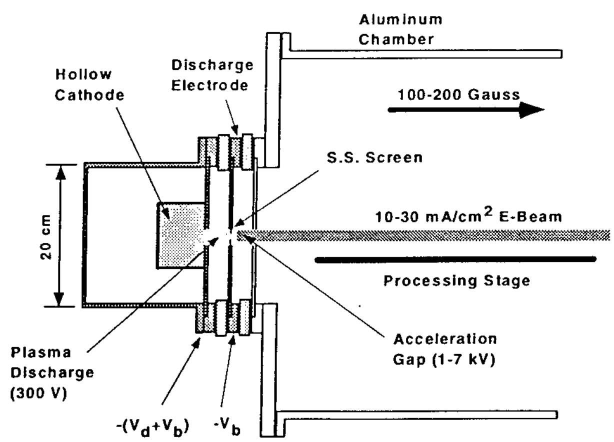

Figure 11. Schematic diagram of the third generation HC system mounted on the test chamber.

Once this system was shown to work with an aluminum box forming the HC, it was modified to elongate the apertures to 15 cm x 1 cm slots and newly designed tubular and rectangular cathode shapes were tested in an effort to produce a uniform plasma profile across the width of the slot. Figure 13 shows several rectangular and tubular profile HC designs which were tested for the uniformity of the sheet plasma they produced.

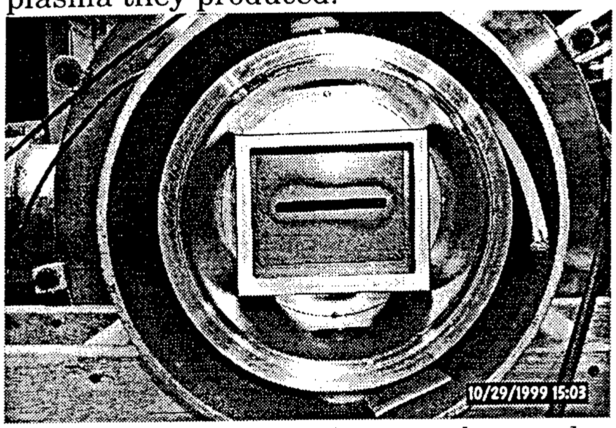

Figure 12. 3" x 4" x 6" aluminum box used to form HC behind the 10 cm x 1 cm apertures. The end of the box is covered with stainless steel mesh to permit viewing of the plasma formed inside the cathode itself.

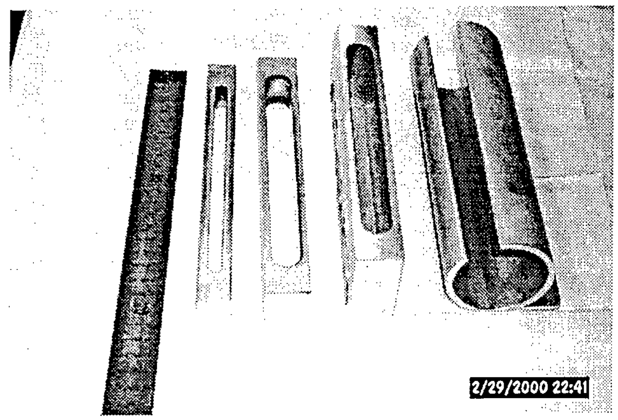

Figure 13. Various tubular and rectangular HC shapes tested after the apertures were elongated to 15 cm x 1 cm in size.

One of the details that emerged from these tests was a relationship between the surface area of the inside of the cathode to the area of the aperture slot. A good rule of thumb was found that the surface area for plasma production inside the cathode should be at least 10x the area of the aperture. Cathodes with a small surface area severely limited the discharge plasma current available in the 1st gap. Raising the cathode power supply voltage did little to raise the output current since the entire surface area of the cathode was already involved in the production of plasma. When the rule of thumb was obeyed, we obtained current vs acceleration voltage characteristics similar to those shown in Fig. 6.

A Langmuir probe was used to measure the plasma uniformity across the width of the sheet. Two beam profiles, one of the worst and one of the best are shown in Figs. 14 & 15 respectively. In Fig. 14, the HC is made from a 2" inner diameter piece of aluminum tubing, while in Fig. 15 the HC is made from a block of aluminum with a 1.6 cm x 16 cm x 2.5 cm slot cut in it. The surface area ratio of the second cathode is a bit below the rule of thumb, but the cathode current was adequate for this test.

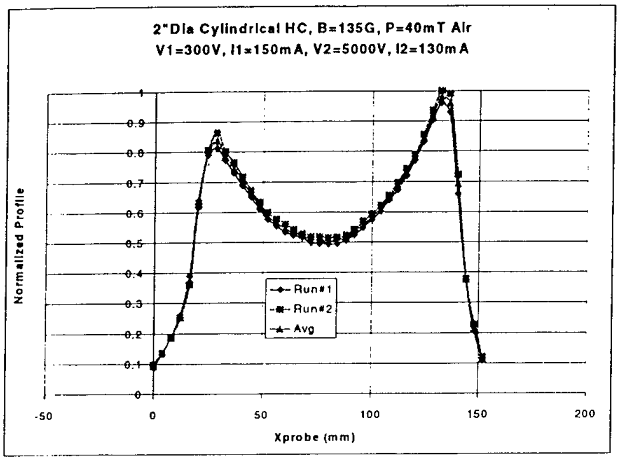

Figure 14. Beam profile from a 2" diameter, tubular HC.

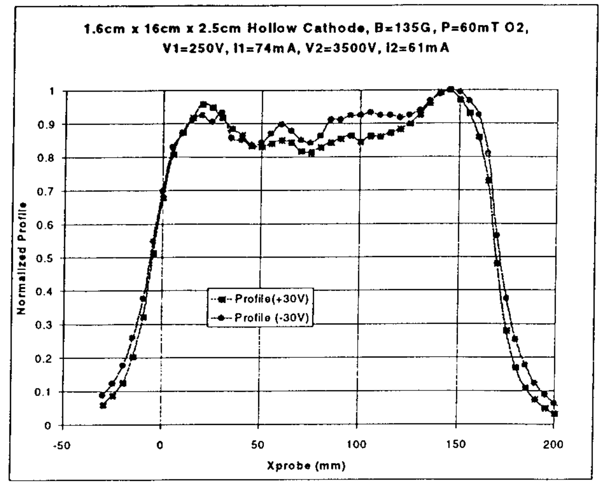

Figure 15. Beam profile from a 16 cm long by 1.6 cm high by 2.5 cm deep HC.

A Langmuir probe was also used to measure the plasma density and the electron temperature in the center of the beam for different fill gases. The results for argon and oxygen are shown in Figs. 16 &17 respectively. Peak ion densities for argon were $N_i \approx 5x10^{13}$ cm^{-3} with electron temperatures of $T_e \approx 0.3-0.8$ eV. For oxygen the density was lower and the temperature higher with $N_i \approx 1.5x10^{12}$ cm^{-3} and $T_e \approx 1-1.5$ eV. These results are in rough agreement with theoretical predictions of the plasma density and temperature.[5] The only significant plasma loss mechanism in argon is diffusion. Argon's first excited state is at 11.55 eV. Moreover, electron cooling is slow. Recombination is the dominate plasma loss mechanism for oxygen. Figures 18 & 19 show an external view of the 10 cm slotted cathode and a side view of the beam inside the test chamber.

[5] R. F. Fernsler, private communication.

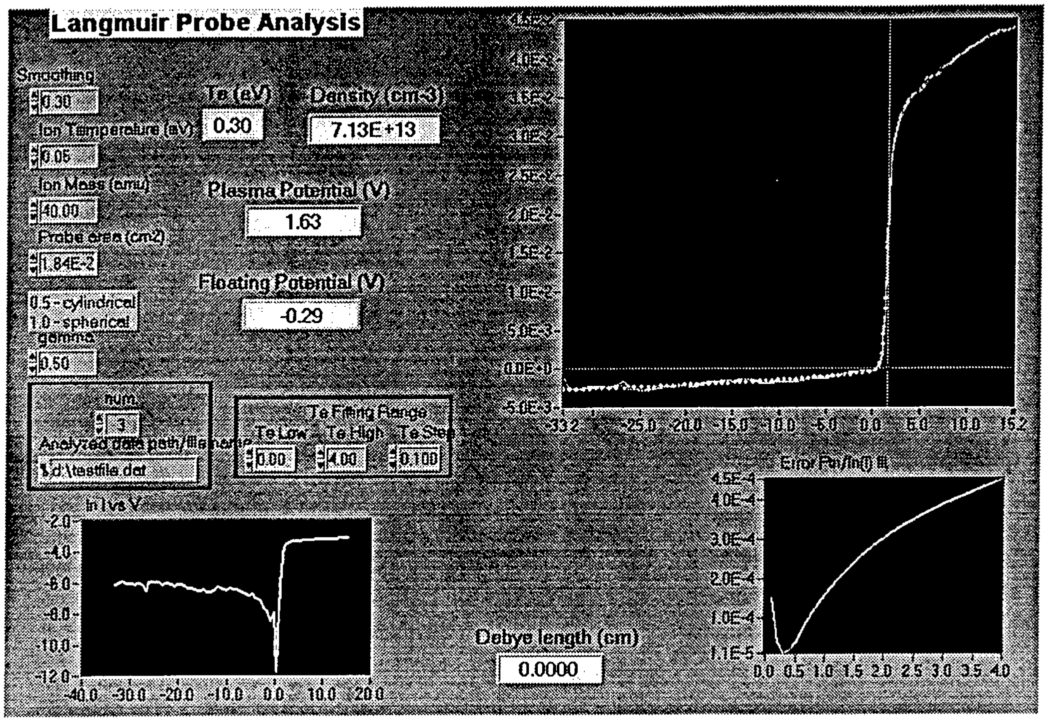

Figure 16. Langmuir probe analysis of argon plasma. P=58mTorr Ar, B=250G, V1=295V, I1=190mA, V2=4500V, I2=150mA

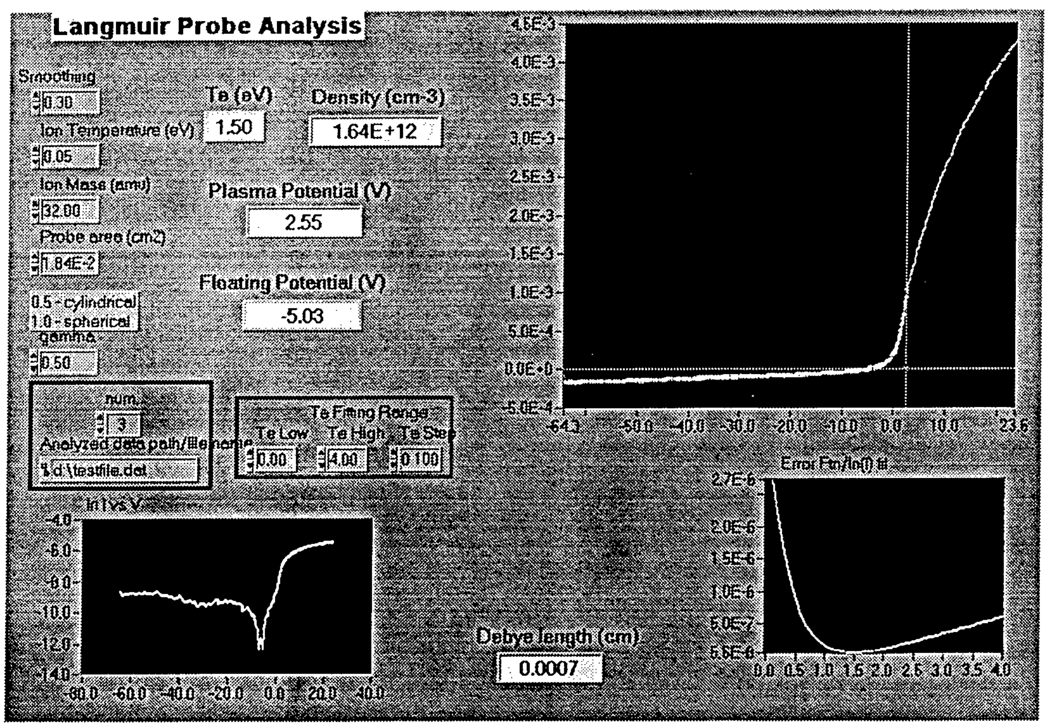

Figure 17. Langmuir probe analysis of oxygen plasma. P=58mTorr O_2, B=250G, V1=285V,I1=200mA, V2=3500V, I2=174mA

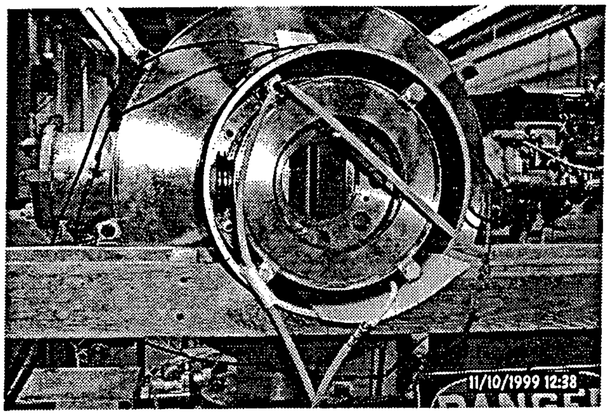

Figure 18. External view of the 10 cm x 1 cm slotted HC.

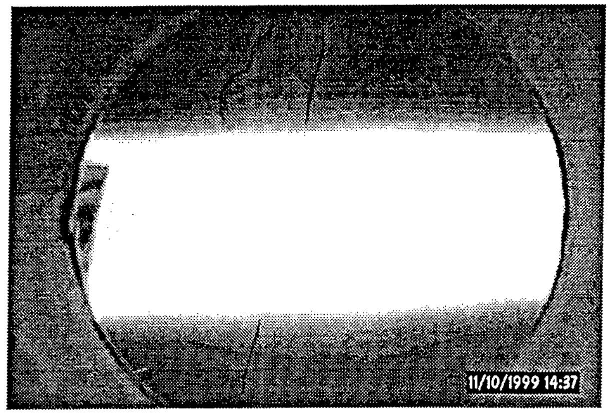

Figure 19. Side view of the 10 cm wide beam inside the test chamber.

30 cm x 1 cm Slotted Source

The latest version of the CW HC has just been installed on the test chamber (see Fig. 20). At 30 cm, this is as wide a source as the test chamber can accommodate. The next larger cathode will have to be tested on the LAPPS chamber itself. The external aluminum housing is 8 cm x 12 cm x 35 cm and can be used as the HC alone or have other shape cathodes installed inside it, such as shown in Figure 13. New diagnostics will be fielded on this plasma source such as the Hyperbolic Energy Analyzer (HEA) and the RF-compensated Langmuir probe that can be used when an RF bias field is applied to the plasma sheet. Figure 21 shows an end-on view of the 30 cm x 1 cm plasma sheet inside the chamber along with a powered, RF bias electrode on one side of the plasma and a ground plane electrode on the other side of the plasma sheet. The RF-compensated Langmuir probe is sticking into the plasma through the ground plane electrode.

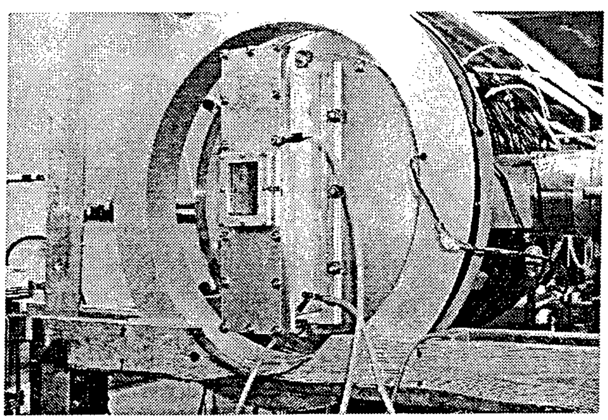

Figure 20. External view of the 30 cm x 1 cm slotted HC assembly.

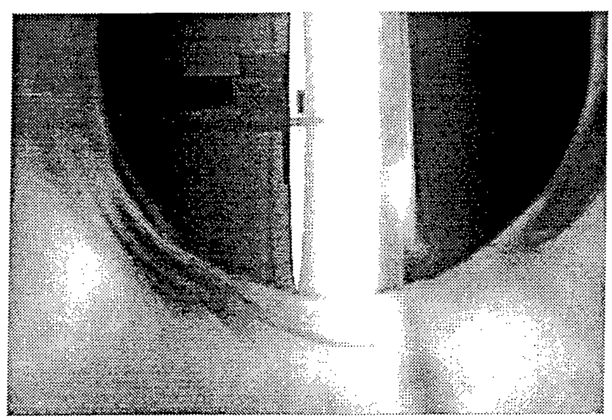

Figure 21. End-on view of the 30 cm x 1 cm plasma sheet bracketed by a ground plane electrode and a powered, RF bias electrode. A Langmuir probe is inserted into the plasma through the ground plane electrode.

Summary
Development of a CW HC plasma source for the LAPPS machine has been through four design generations. The beam profile across the width of the plasma sheet is not uniform enough for the LAPPS machine requirements but the 30 cm wide cathode has yet to be thoroughly tested. Plasma density and temperature measurements in oxygen and argon agree roughly with theoretical predictions. Further tests on the reaction of the plasma sheet to the presence of an RF bias field are scheduled. The CW HCs tested so far are capable of operation for extended periods. Overheating of the external magnets on the aluminum test chamber is the limiting factor for run times of more than one hour at present.

Acknowledgement
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